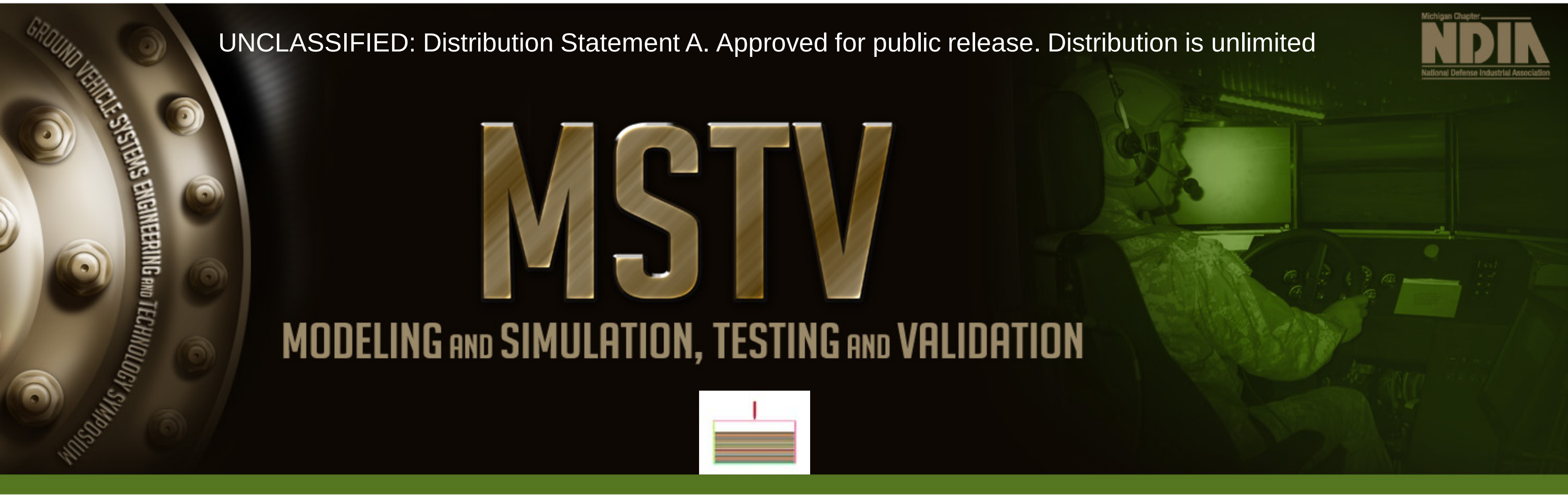

BAllistic SImulation Method for Lithium Ion Batteries(BASIMLIB) using Thick Shell Composites (TSC) in LS-DYNA

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Motivation & Background

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Motivation/Technical Background

- There are four main causes of battery failure
  - Mechanical, Electrical, Thermal & Immersion
- The DOE's Vehicle Technologies Office (VTO) initiated the Computer Aided Engineering for Electric Batteries (CAEBAT) activity in FY 2010 and TARDEC joined the efforts to co-sponsor the program with more focus on battery performance at extreme conditions and mechanical destructive behavior
- National Renewable Energy Laboratory (NREL) has been actively in the CAEBAT from the inception
- MIT has been studying the mechanical properties and behavior of the cells through experimental and modeling at their crash worthiness laboratory
- Most of the simulation work on the batteries are at a single cell level and gap exists to simulate the batteries at their full pack capacity
  - Firstly, requires an enormous amount of computational capability due to very large number of elements associated in modeling the full pack
  - Secondly, thickness of the anode, cathode, and active materials are in micro scale, adds more complexity in modeling such a small scale

Objective

- Objective and focus of this work is to develop a
  - Robust simulation methodology to model lithium-ion based batteries in its module and full pack capacity
  - Evaluate the developed methodology for mechanical failures i.e., bullet impact at oblique, vertical and horizontal loading conditions

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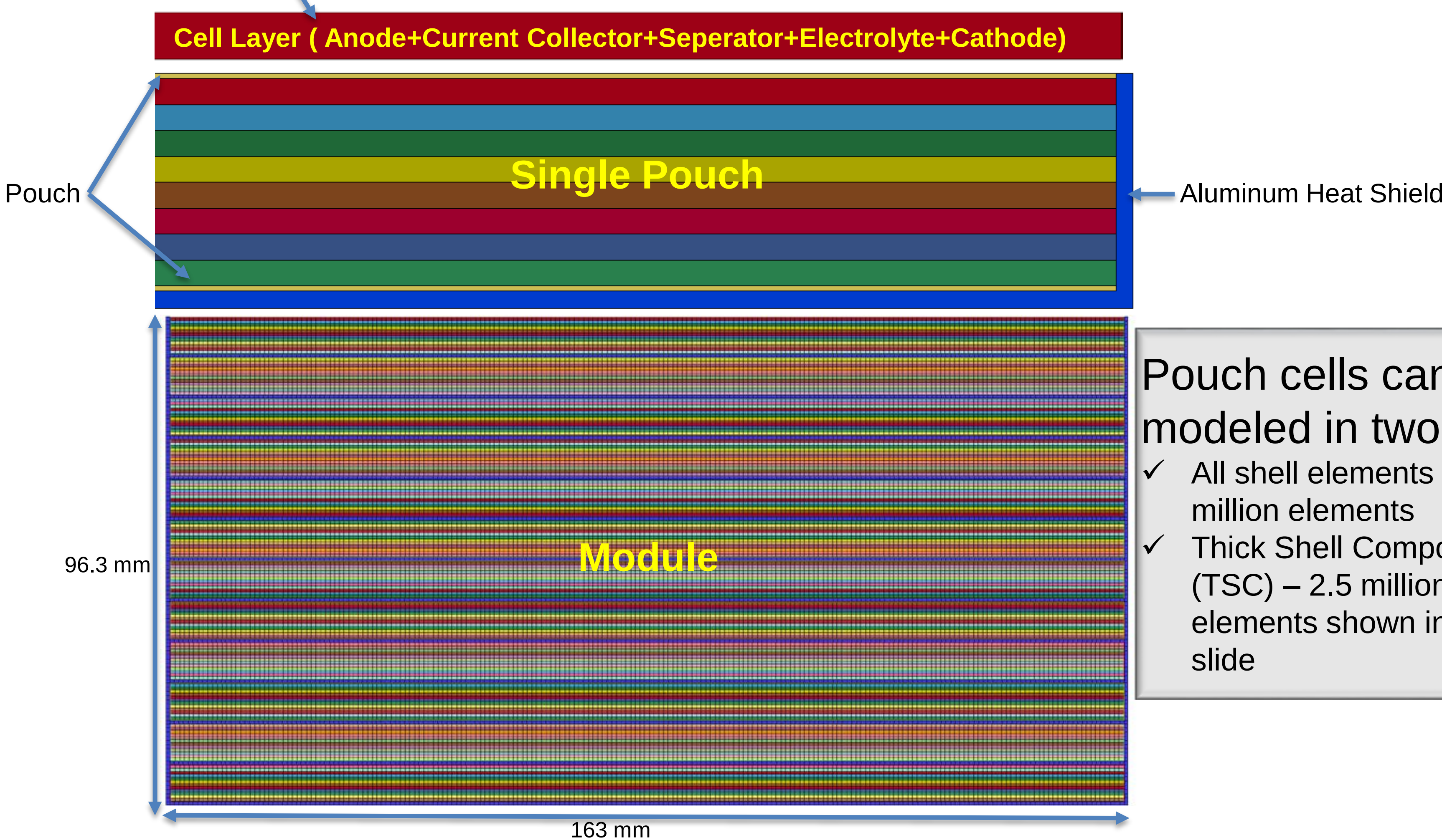
Background

- Component state of understanding
    - ✓ Current collectors well understood
- Electrodes(active material)
    - ✓ not well understood
    - ✓ powder form held together by binders
    - ✓ high degree of porosity
    - ✓ low tensile load capacity
- Separator understood to some extent
- Electrolyte role uncertain
- Mechanics of interfaces between components
    - ✓ unknown

Information from http://batterysim.org/ Oak Ridge National Lab SAE 2015 government /industry meeting

BASIMLIB
Battery model



Pouch cells can be modeled in two ways

- ✓ All shell elements – 12.5 million elements
- ✓ Thick Shell Composites (TSC) – 2.5 million elements shown in this slide

<u>Battery Layer, Pouch & Module construction</u>

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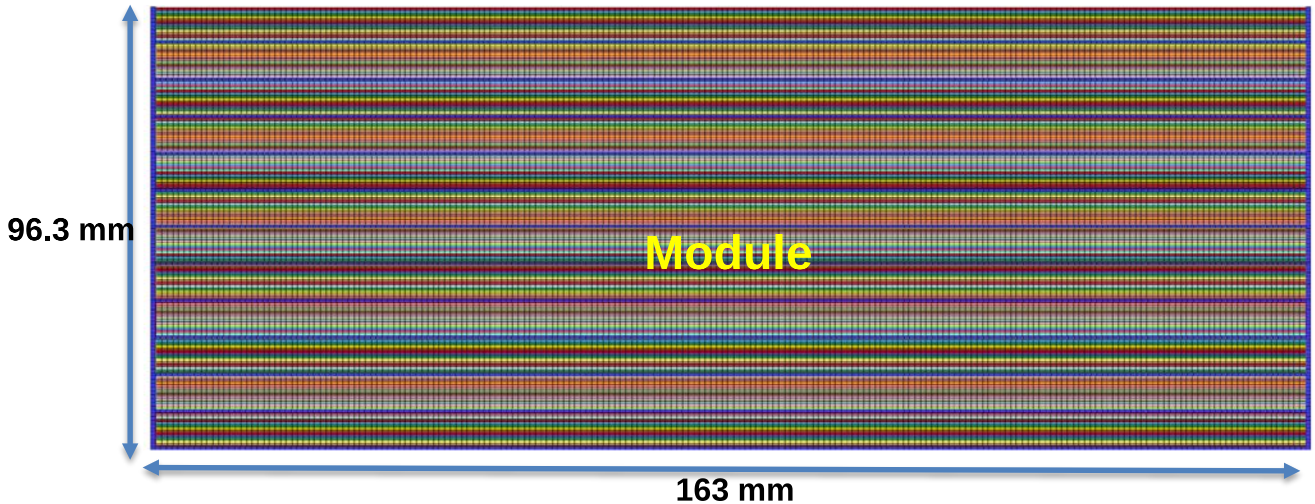
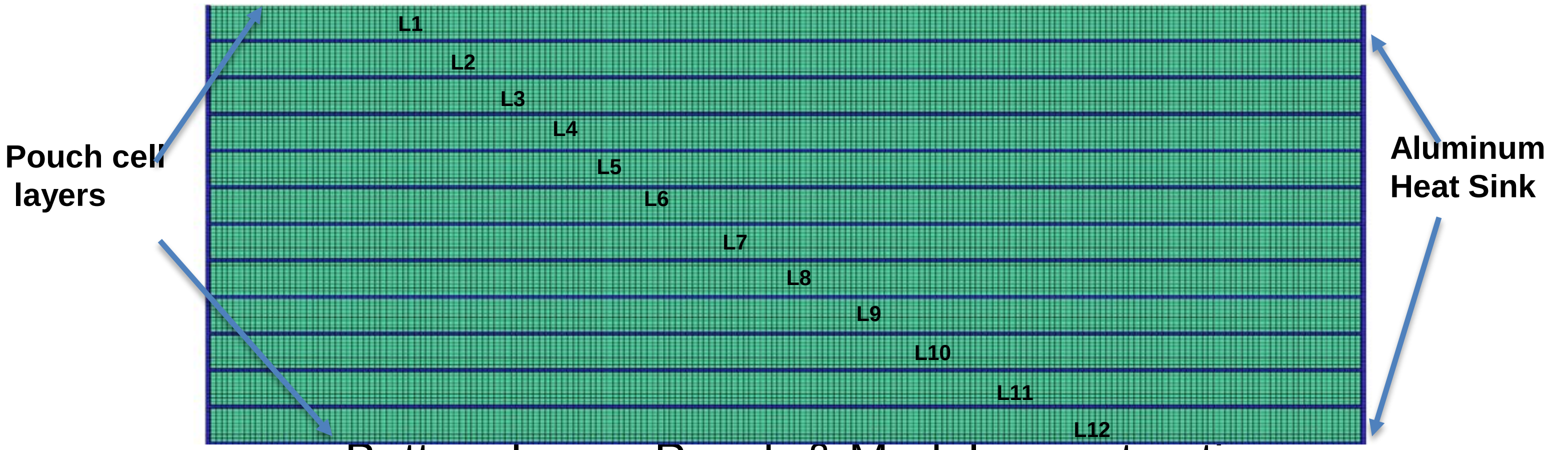
Battery module model





Battery Layer, Pouch & Module construction

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Battery Layer Thicknesses

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Positive Current Collector (Aluminum foil) = 20 µ
Graphite Anode = 95 µ
Separator (Polypro) = 20 µ
LiFePO4 Cathode = 100 µ
Negative Current Collector (Copper foil) = 20 µ
Separator (Polypro) = 20 µ

- ✓ General thickness and layer composition of a pouch cell battery is shown above
- ✓ Microscale thicknesses makes it difficult to represent the batteries as a micromechanical model.
- ✓ Thick shell composite part card is shown below.

```
*PART_COMPOSITE_TSHELL
$# LiFePO4
$#      pid    elform      shrf    unused    unused      hgid    unused    tshear
          1         2     0.000                   1         0
$#     mid1    thick1        b1     tmid1      mid2    thick2        b2     tmid2
          1 2.0000E-5     0.000         0         2 9.5000E-5     0.000         0
          3 2.0000E-5     0.000         0         4 1.2500E-4     0.000         0
```

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Battery Material Properties

Mechanical Properties	*Units*	*Aluminum current collector*	*Copper current collector*	*LiFePo4 Cathode*	*Seperator*	*Graphite Anode*	*Brass Bullet*
Density	kg/m*3	2,700	7,583	2,600	1,176	2,200	10,822
Elastic Modulas	Mpa	70,000	110,000	12,500	3,450	32,000	115,000
Yield Stress	Mpa	195	230	10	180	97	896

- Material properties used in this analysis is derived from previous CAEBAT project conducted by Department of Energy’s (DOE) National Renewable Energy Laboratory (NREL)

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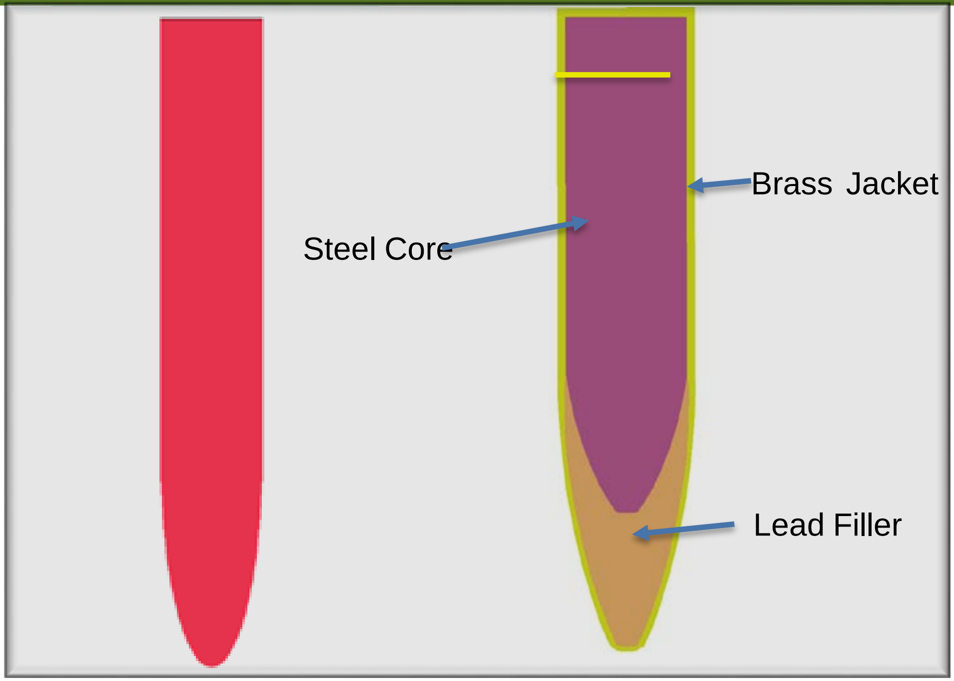
Bullet model



NATO 0.308 Caliber bullet model

- NATO 0.308 caliber full metal jacket with 7.62 mm in diameter and 51 mm in length is used in this analysis
- Initial velocity of the bullet was set at 762 m/s for pouch cell test & 825 m/s for module test
- DEFINE_ADAPTIVE_SOLID_TO_SPH is activated to capture the fragmenting bullet particles

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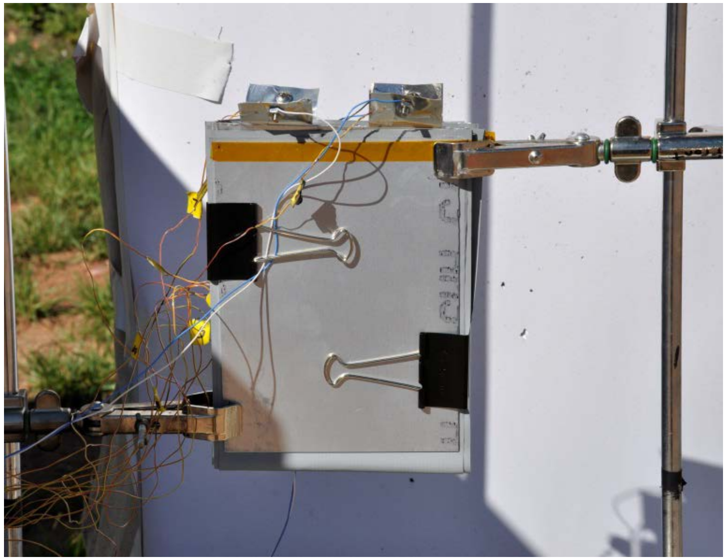
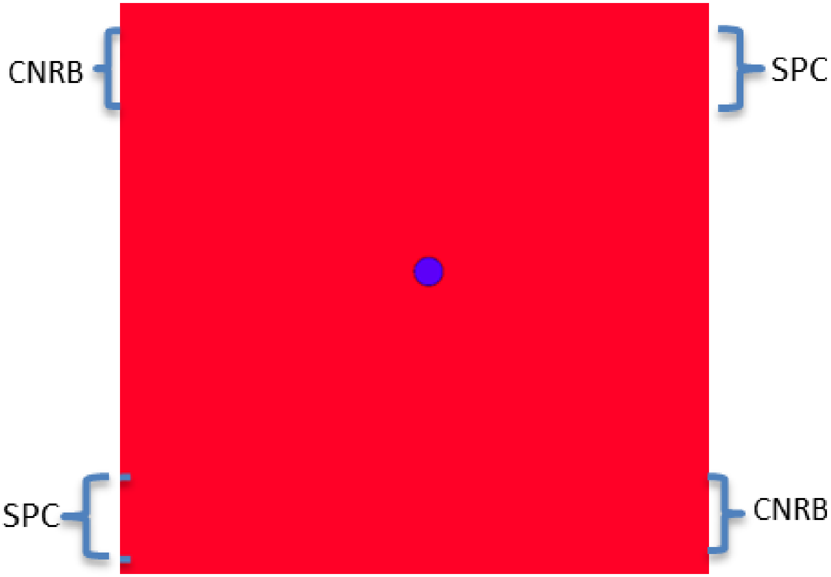
Ballistics two cell battery setup



Test



M&S

TEST & M&S model set up for pouch cell bullet impact shown above

- ✓ CNRB (Constrained Nodal Rigid Bodies) represents two clips top left and bottom right which are free to move and or rotate depending upon the load
- ✓ SPC (Single Point Constraints) represents two clips bottom left and top right as fixed boundary conditions

Model set up of pouch cells bullet impact

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Ballistics two cell battery setup

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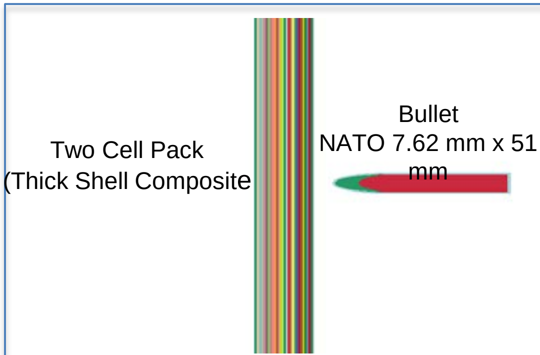
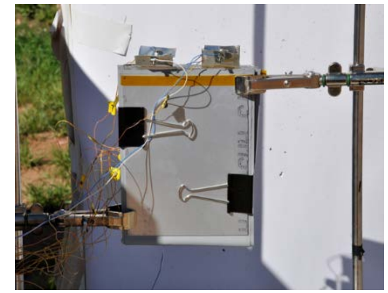
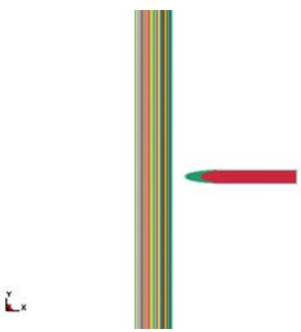


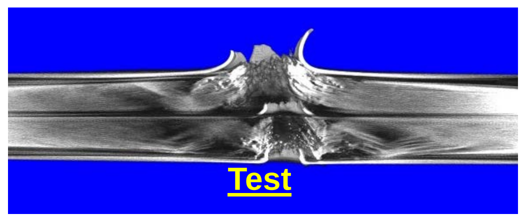
Bullet Specification
- 308 Caliber Ammunition
  - 7.62mm x 51mm
  - Full Metal Jacket
  - 2500 FPS (762 m/s) Velocity



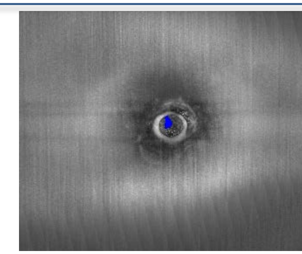
Test

Bullet impact

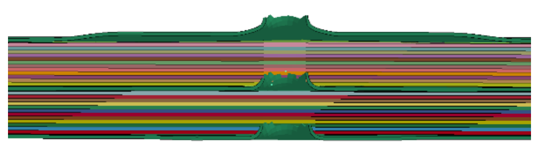




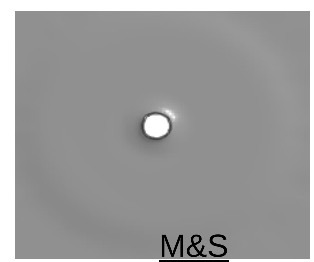
- Aluminum cell separator penetrated into electrodes



Test



M&S



Model set up, animation and deformed cells

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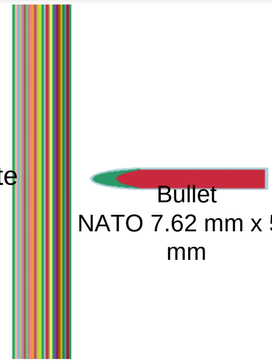
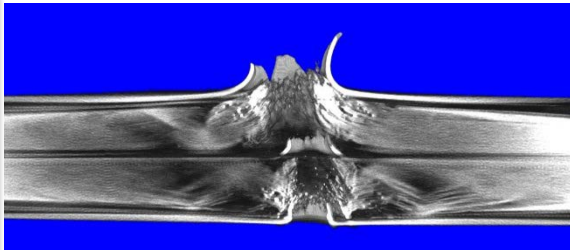
Ballistics two cell battery setup

Two Cell Pack
(Thick Shell composite)



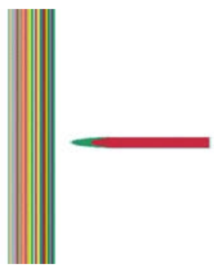
Bullet
NATO 7.62 mm x 51 mm

- Both Thick Shell Composite and Thin Shell Layer models captures the ballistics impact
- Number of elements
  - ✓ Thick Shell Composite = 2.5 million
  - ✓ Thin Shell Layer = 12.5 million

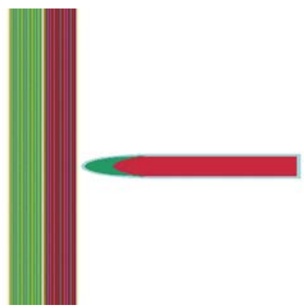


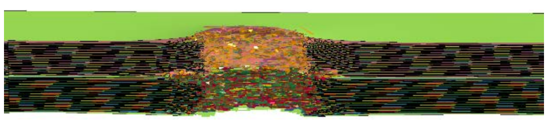
- Aluminum cell separator penetrated into electrodes

Bullet impact
(Thick Shell Composite)

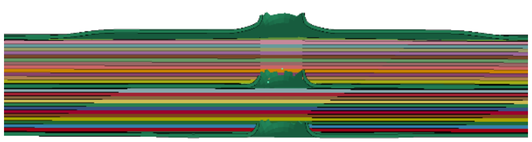


Bullet impact
(Thin Shell Layers)





M&S (Thin Shell Layers)



M&S (Thick Shell Composite)

Model set up, animation and deformed cells

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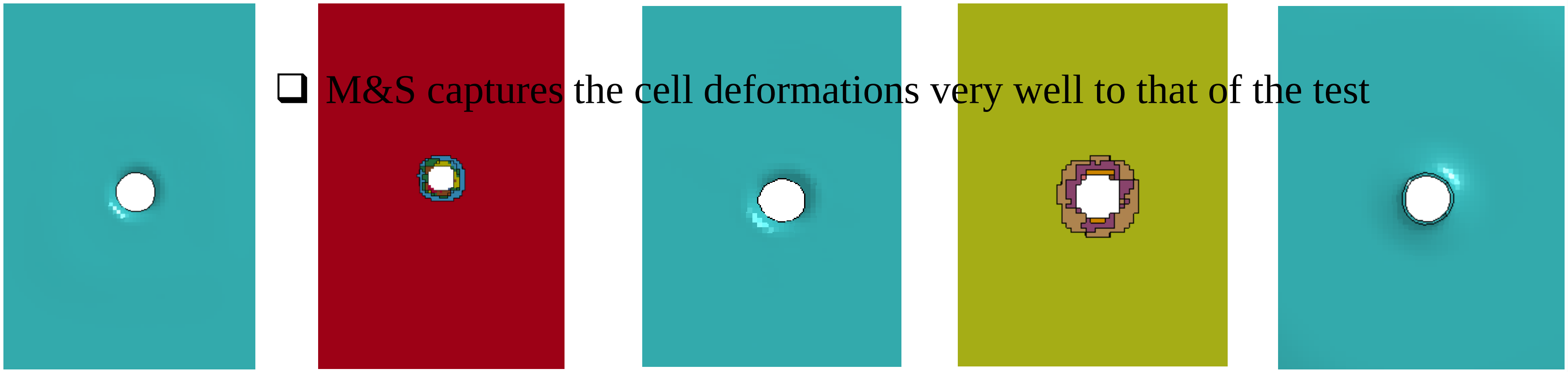
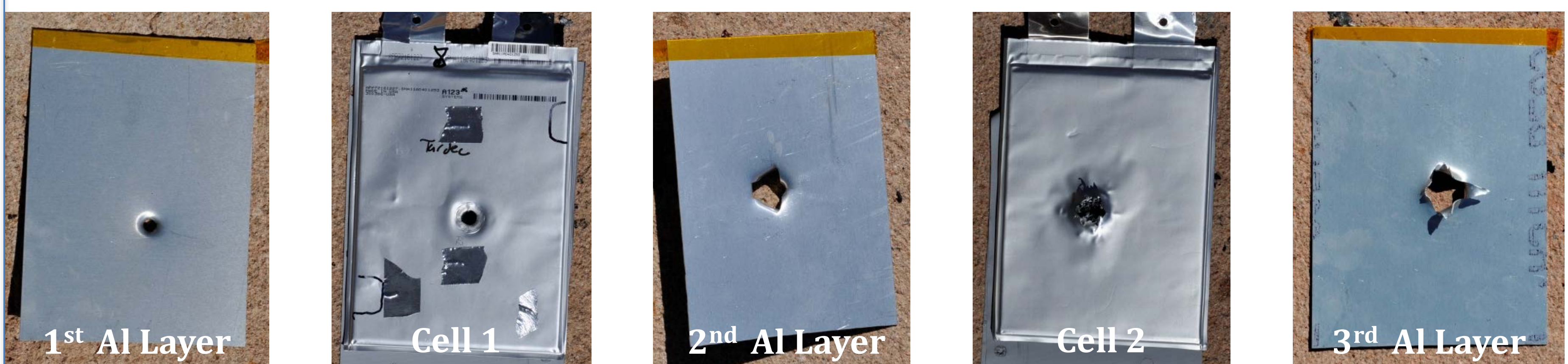
Ballistics Cell Deformation

- M&S captures the cell deformations very well to that of the test



M&S



Test

Cell and layer deformations

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Ballistics system level setup

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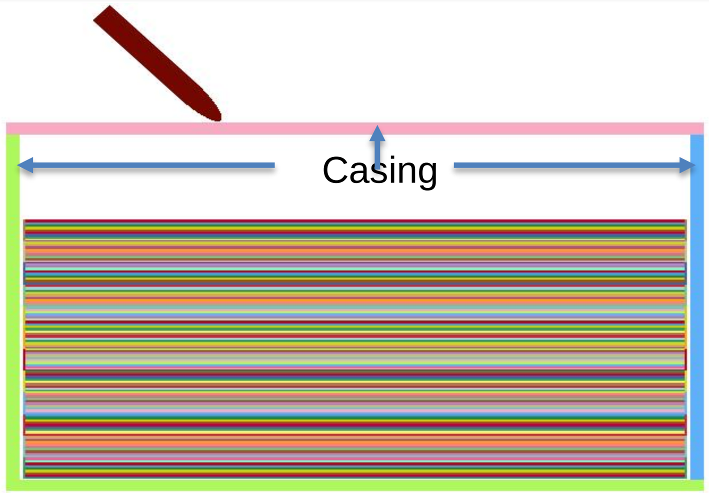
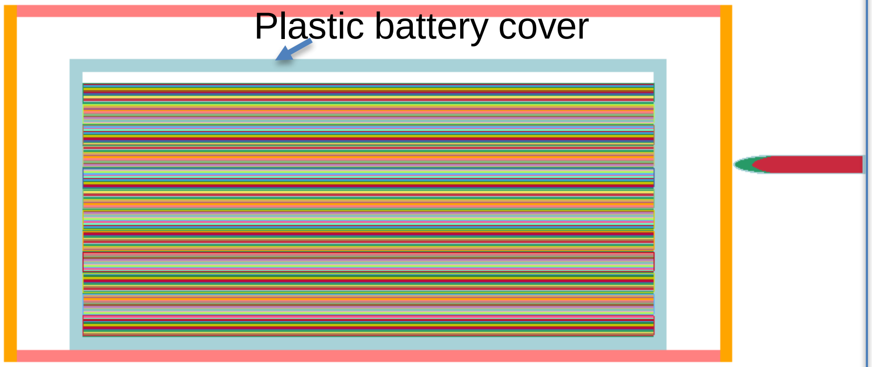
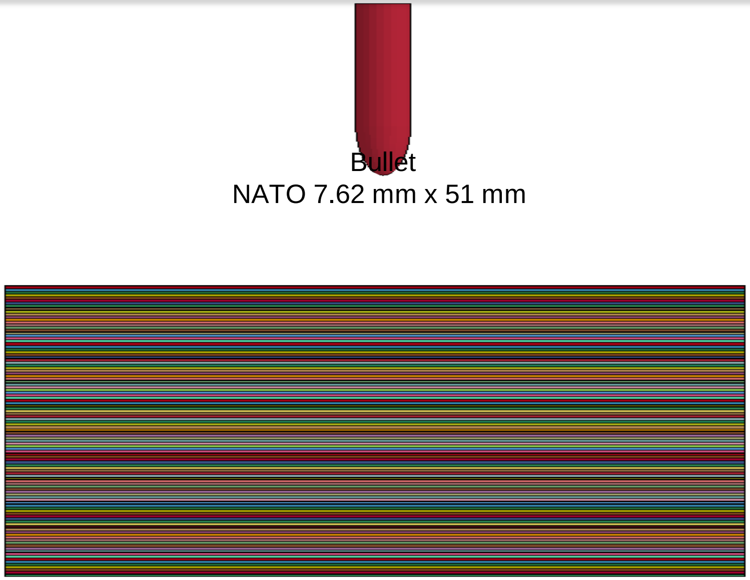


45 Degree oblique impact



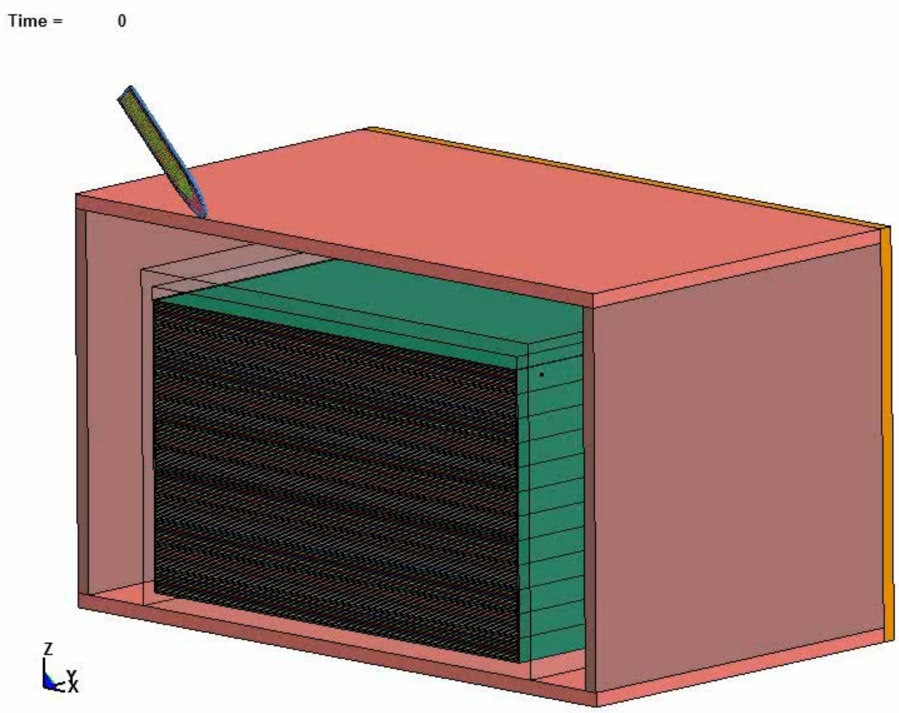
0 Degree horizontal impact

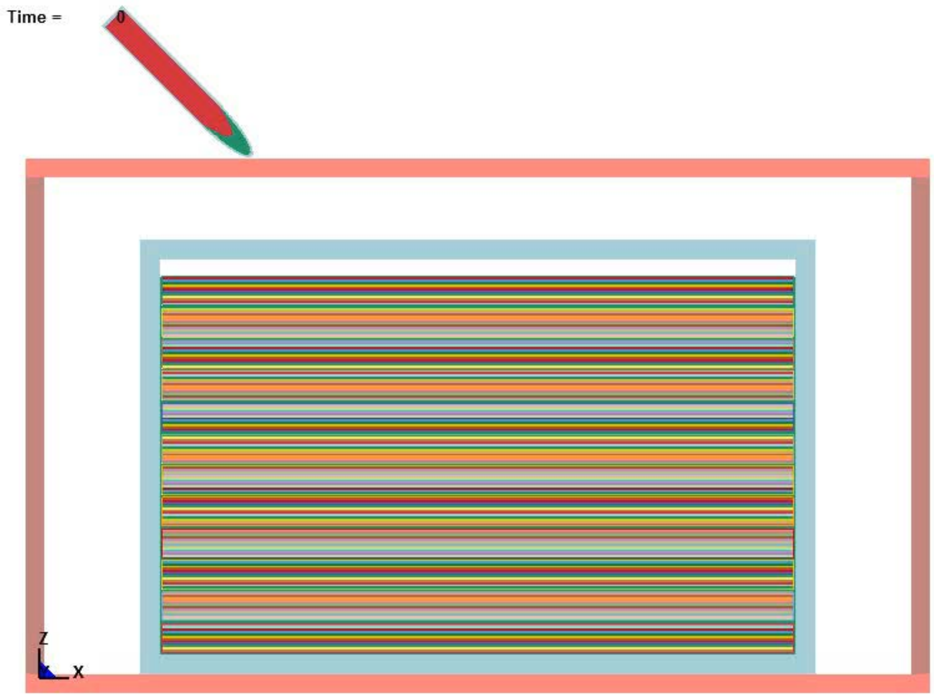
- o Full battery module with 1762 layers was impacted with three different loading conditions
  - ✓ *Vertical impact*
  - ✓ *Oblique impact @ 45 degrees*
  - ✓ *Horizontal impact*
- o Casing represents generic vehicle structure.
- o Analysis was perfumed with two casings
  - ✓ *Case1 – 1" RHA*
  - ✓ *Case2 – 1" Aluminum*



90 Degree vertical impact

BASIMLIB – Oblique impact animation





Animation of 45 deg oblique bullet impact with Aluminum Structural Enclosure

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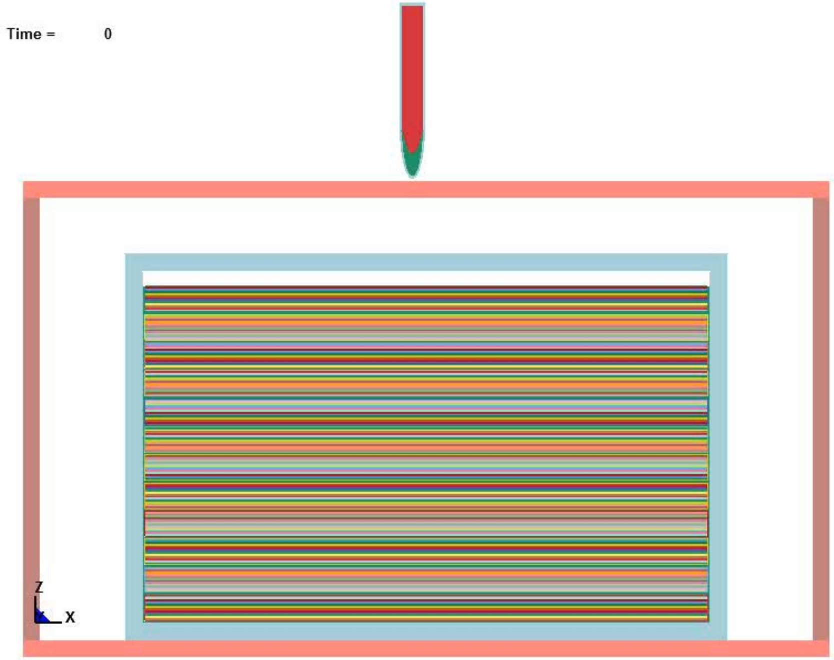
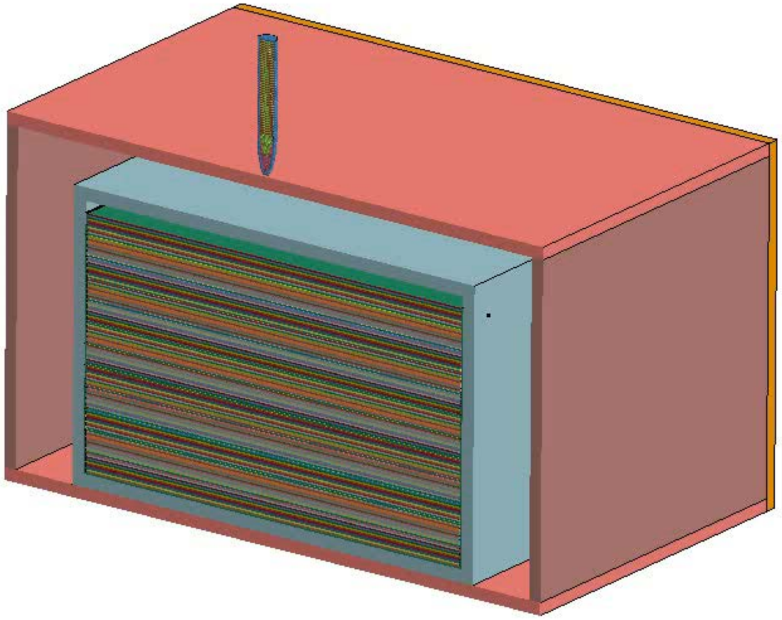
90 Degree impact animation





Animation of vertical bullet impact with Aluminum Structural Enclosure

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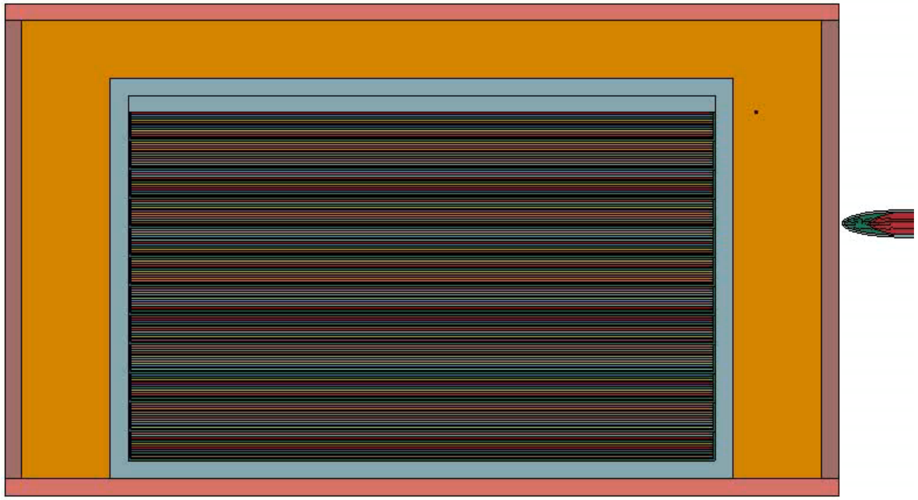
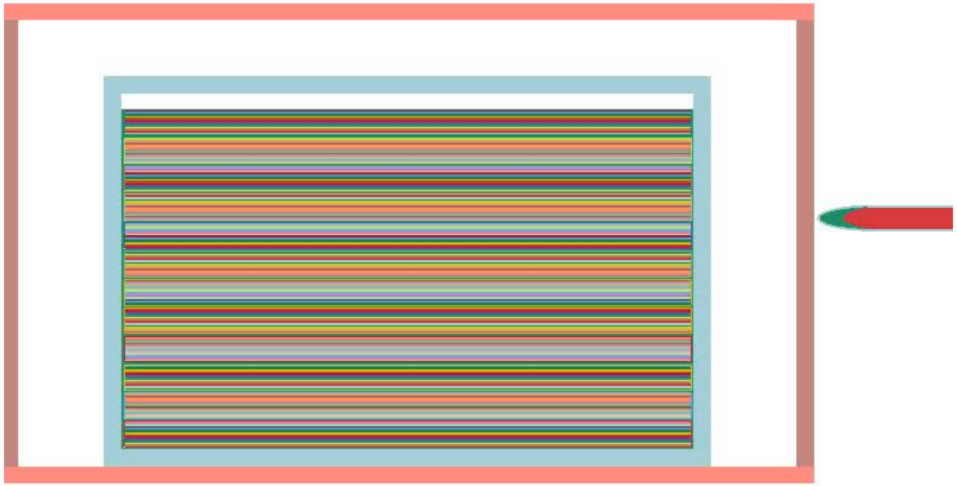
Zero degree lateral impact animation





Animation of horizontal bullet impact with Aluminum Structural Enclosure

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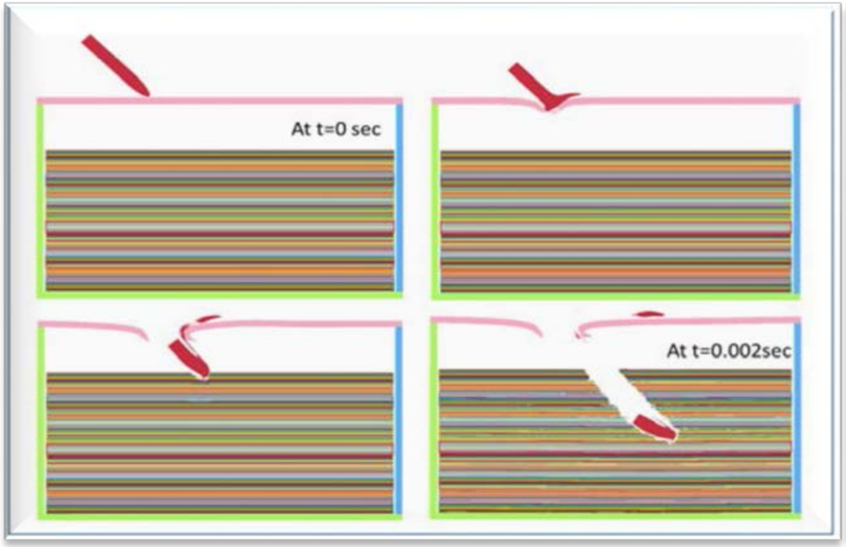
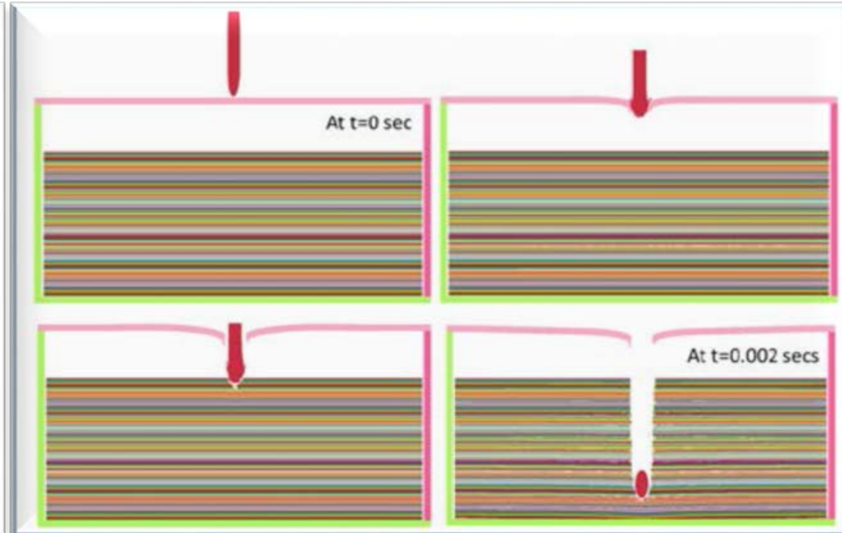
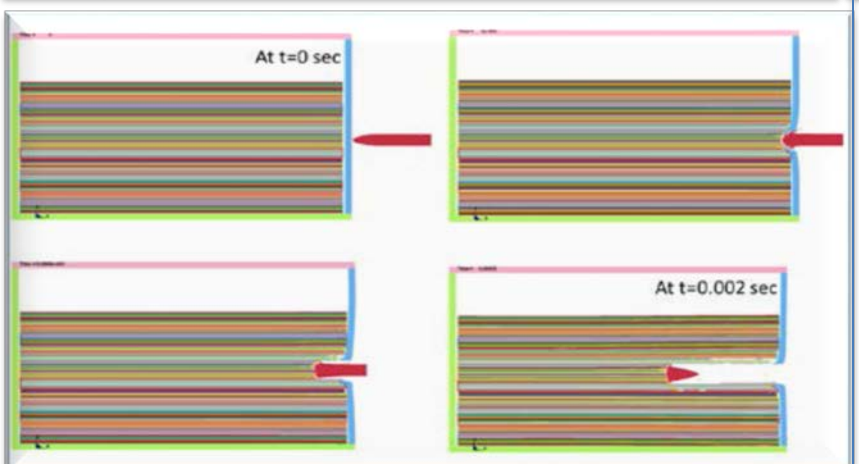
Deformed Cell Layers with RHA Casing







- ❑ Bullet penetration for RHA casing
  - ✓ Vertical impact – 80% of the module
  - ✓ Oblique impact – 45%
  - ✓ Horizontal impact – 30%
- ❑ Shock waves from the bullet impact damages the electrodes throughout the entire cells in the module.

BASIMLIB – *Summary & Conclusion*

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- Lithium Ion Phosphate (LiFePO4) battery cell, module and pack was modeled in LS-DYNA using both Thin Shell Layer (TSL) and Thick Shell Composite (TSC) methodology. This approach can be applied to other Lithium based battery chemistry
- Three bullet loading conditions were considered, 90 degree vertical, 45 degree oblique and zero degree horizontal
- Both TSL and TSL battery methods are correlated to a two cell ballistic test successfully for mechanical failures. Thermal runaway and short due to electric shock was not considered in this simulation
  - ✓ Thickness of Li-Ion batteries layers were modeled at micro scale.
  - ✓ NREL provided Anode, Cathode, Separator and electrode properties were used in this model
  - ✓ Vehicle enclosure is modeled with RHA steel with Johnson-Cook strength and failure material model.
  - ✓ Battery module is enclosed in a plastic casing.

BASIMLIB – *Summary & Conclusion*

- Strong anisotropic deformation behavior of battery cells are captured in all the loading cases are shown in slides 3, 4, 5
- Shock waves from bullet impact damages the electrodes throughout the entire cells in the battery module in all the three loading conditions.
  - ✓ This may result in high temperature and thermal runaway.
- Thick Shell Composite model has 2.5 million elements compared to 12.5 million elements for Thin Shell Layer model per pouch cell.
  - ✓ One battery module was represented with 12 pouch cells with 1,768 layers consisting of positive & negative current collectors, anodes, cathodes (LiFePo4), separators and electrolytes) using TSC

BASIMLIB

Acknowledgements;

Authors would like to thank

Shriram Santhanagopalan of NREL,
Larry Toomey of the TARDEC Energy Storage Team,
Madan Vunnam of the TARDEC Energetic Effects and
Joe Raymond of the TARDEC Computational Methods and System Behavior Team.

Thank You